SEISMIC AND INFRASOUND DATA AND MODELS AT NEAR-REGIONAL DISTANCES

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ABSTRACT

The Korean Peninsula provides a unique laboratory for studying regional seismic and infrasound wave propagation. Numerous broadband seismic stations in the region and a variety of natural and man-made sources provide opportunities for characterizing wave propagation and source effects. The region includes two arrays, KSAR and CHNAR (the seismo-acoustic array near Chulwon operated by Korea Institute of Geosciences and Mineral Resources and Southern Methodist University). The purpose of this research is to investigate how array and network data with ground truth can be used in characterizing source and propagation path effects for seismic and infrasonic waves. Ground truth information plays a critical role in the interpretation of signals and has included near-field observations from industrial blasts, newspaper accounts of accidental explosions, blast design information for mine explosions and near-field observations of earthquakes. Mining blasts in the Republic of Korea are constrained to about 2000 kg. Combining design pattern information and near-source observations illustrates that peak amplitudes of regional seismic phases are greatly reduced from those expected for a contained single-fired explosion. At CHNAR an average of three to four seismic events and one seismo-acoustic event are observed per day.

Analysis of the infrasound data suggests that there are many more infrasound signals than seismic. For example, during a one-week time period over 400 infrasound events were recorded. These data motivated an in-depth analysis of the lonesome infrasound signals. Based on infrasound signals that accompany seismic signals, we believe that many of the infrasound sources are within 200 km of the array (near regional). We have modeled these arrivals using an infrasonic modeling program (InfraMAP) employing three data sets: Horizontal Wind Model and Mass Spectrometer, Incoherent Scatter (HWM/MSIS) data, hourly meteorological data, and daily mean meteorological data. Hourly data were broken down into six hourly blocks at Hour 0, Hour 6, Hour 12 and Hour 18 and obtained by weather balloon from OSAN Air Force Base, 131 km to the south of CHNAR. MSIS/HWM models predict no arrivals closer than 250 km during this time period. Mean daily data predict arrivals at around 18-20 km and actual hourly data predict arrivals almost on top of the source, as close as 0.5 km away. Comparing back azimuths observed with back azimuths predicted by infrasonic ray path modeling, we note that the hourly data accurately predict the arrival back azimuths. This leads us to believe that hourly meteorological data are of immense importance when considering infrasonic arrival predictions for near-regional distance.

OBJECTIVE:

The seismo-acoustic array, CHNAR, in the Republic of Korea was installed in the far north of the Republic of Korea for the purposes of determining the numbers and types of signals that are observed on both seismic and infrasound sensors (Stump *et al.,* 2000). Southern Methodist University (SMU), in cooperation with Korea Institute of Geosciences and Mineral Resources (KIGAM), jointly operate the array and conduct research on the resulting data. This cooperative work began with a preliminary study of events (Figure 1a) that has been summarized by Stump *et al.,* 2001. This work suggested that the array recorded some three to five seismic and one seismo-acoustic event each day. As illustrated in Figure 1a, the events clustered into groups. Nearly all the seismo-acoustic events were found to occur during working hours indicative of man-made causes. Additionally, as Figure 1a suggests, many events in both North and South Korea were found to be within 200 km of the array. This range is not fully understood from theory as typical infrasound propagation models predict few if any arrivals in this distance range.

These early results motivated supporting work to gather ground truth information for sources that produced signals at CHNAR. A number of procedures were undertaken to establish the ground truth, including the acquisition of near-source ground motions from mining events, documentation of construction blasting through video records or engineer notes, press documentation of accidents, and near-source ground motion records of earthquakes. Figure 1b illustrates some of this ground truth information with its spatial distribution across the Korean Peninsula.

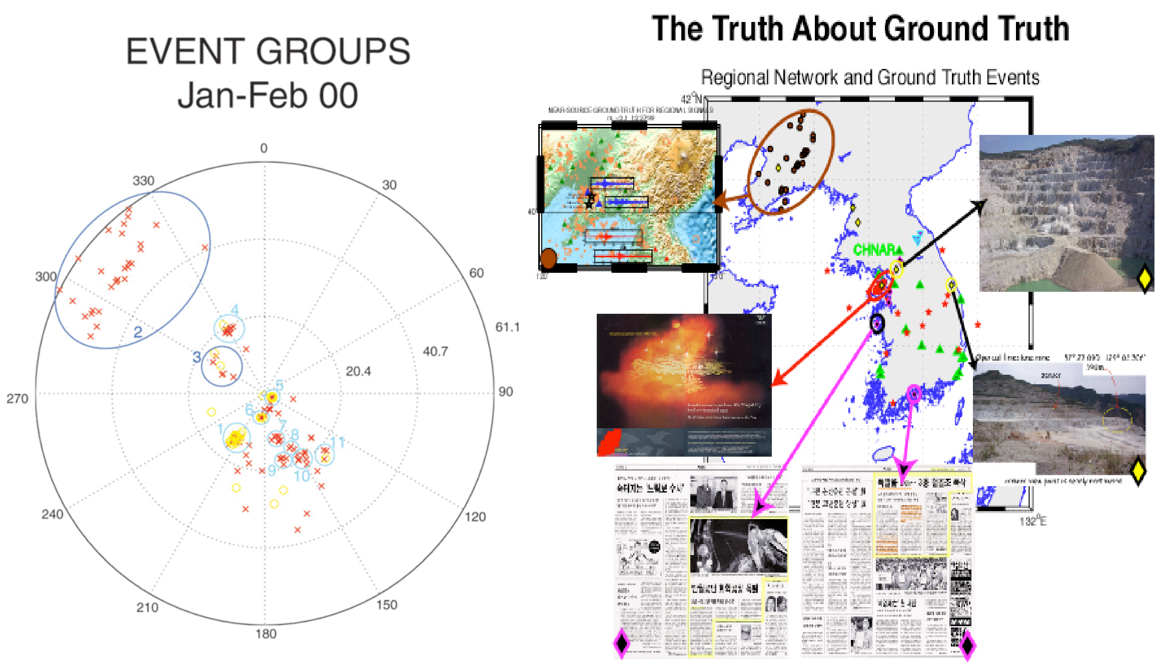

Figure 1a: Preliminary locations of seismic (red x) and seismo-acoustic (yellow o) events located using data from CHNAR (Stump *et al.,* 2001). The locations are plotted as a function of back azimuth and L_g-P time (s) that can be converted to range (km) by multiplying by 8. 1b: Examples of ground truth for events recorded at CHNAR. Earthquake – brown circles; Construction blasts – red squares; Accidental explosions – black and purple diamonds; Mining explosions – yellow and black diamonds.

Based upon these preliminary results, a comprehensive study of seismo-acoustic events has been undertaken by Il-Young Che at KIGAM. All the seismo-acoustic events from this study for the calendar years 2000 and 2001 are documented in Figure 2. In each year, the events in both the north and south cluster into groups as found in the preliminary two-month study. There is an apparent increase in the number of seismo-acoustic events in North Korea during 2001.

The event locations in Figure 2 are based upon the seismic arrival times and back azimuth estimates using the data from all the stations of the KIGAM network. Preliminary locations are completed automatically, but an analyst reviews all final locations. There are many times more seismic-only events that are not plotted in this figure. We also note that there are many more infrasound alone signals than seismo-acoustic signals.

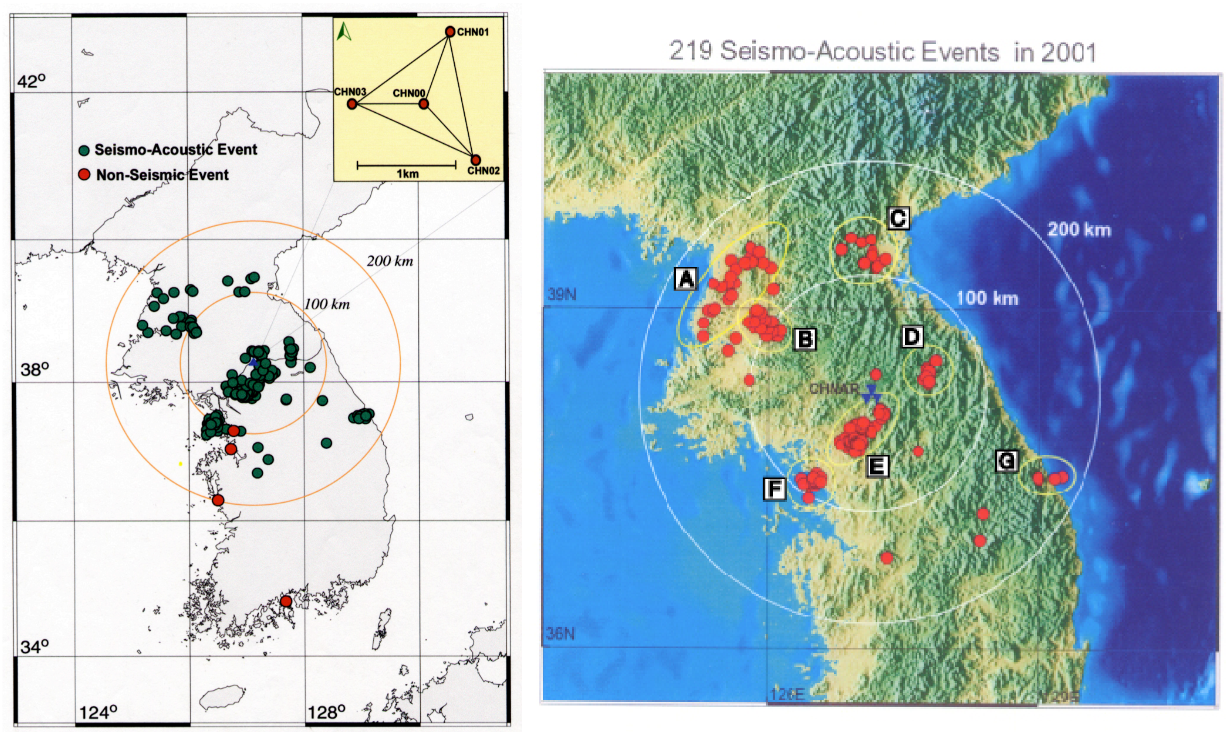

Figure 2a: Seismo-acoustic events for 2000. 2b: Seismo-acoustic events for 2001. Event location is based upon arrival times and back azimuth estimates using data from all the seismic stations in the KIGAM network. Based upon the location, a search is made for a complementary acoustic signal at CHNAR in order for the event to be designated as seismo-acoustic (Figures from I.-Y. Che, KIGAM).

The events plotted in Figures 2a and 2b are all within 200 km of CHNAR. The 2001 data are divided into seven groups for purposes of analysis and are designated Groups A-G in Figure 2a.

RESEARCH ACCOMPLISHED

Ground Truth

We illustrate ground truth information from some of the event groups in Figure 2b.

Seismo-acoustic events in Group E southwest of CHNAR represent a number of hard rock mines in South Korea. Ground truth information was acquired from several of the mining shots in this region. As noted earlier, most of these shots use modest amounts of explosives and are delay-fired. The blast design information and in-mine seismic measurements for one of these events are reproduced in Figure 3. In this shot, a total of 2980 kg of explosives was detonated using 17- and 42-ms delays.

We produced an impulse time series representative of this delay pattern. The spectrum from this model is compared to the double integrated near-source accelerogram indicating that the impulse time series is reflective of the source. The model and near-source displacement spectra indicate that the regional amplitudes from the delay-fired explosion are reduced in size by a factor of 10-100 from what would be expected from a 2980-kg single-fired explosion. The data at CHNAR from this explosion are also included in the figure illustrating that the signal is just above background noise. Both the limited amount of explosives and the delay-fired pattern may be responsible for the small magnitudes of seismo-acoustic events observed in South Korea. This result suggests that unless the blasting practice is well understood, one should not use waveforms from delay-fired explosions to constrain the relationship between magnitude and amount of explosives.

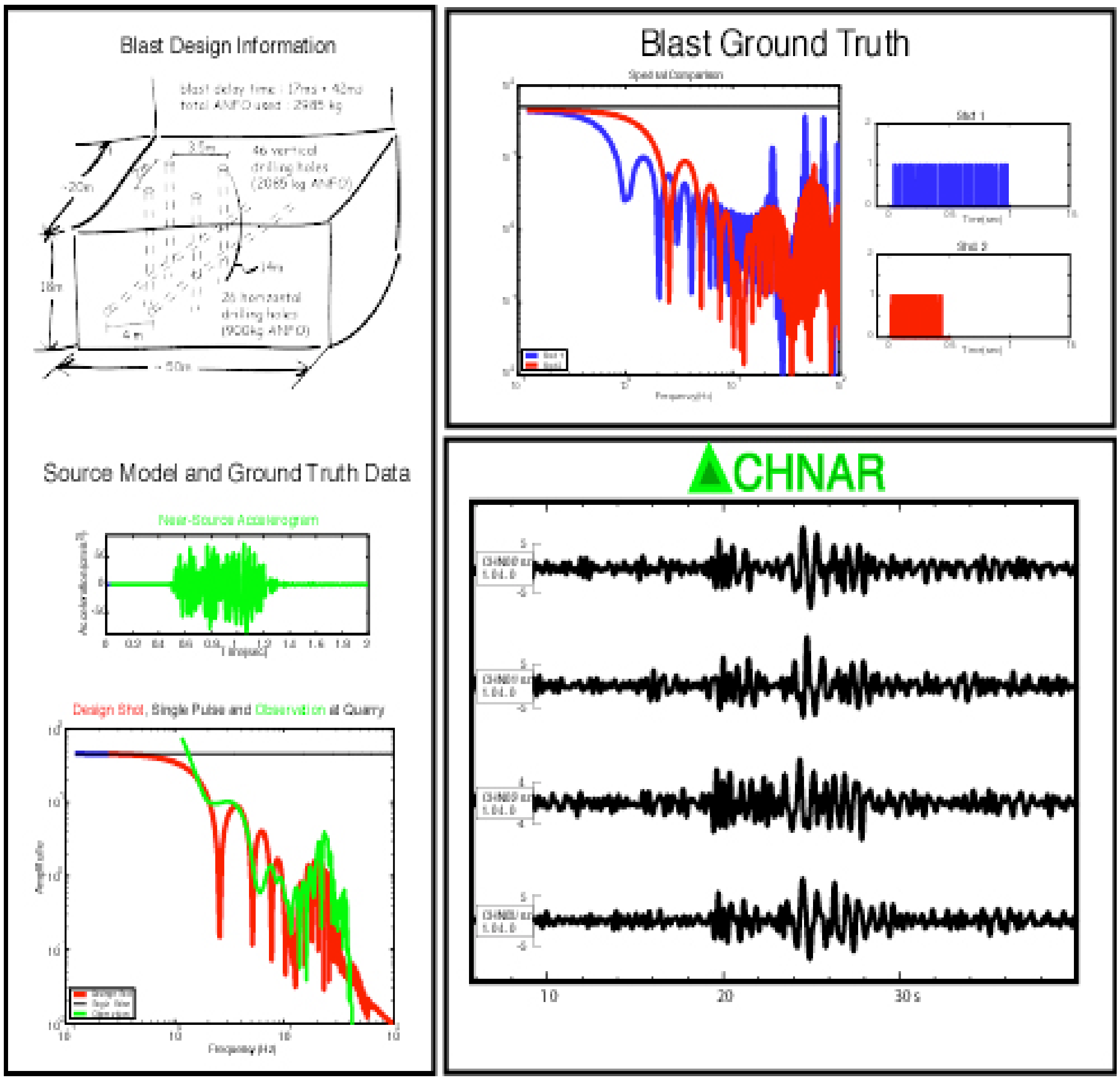

Figure 3: Ground truth from a mining explosion in Group E. The ground truth includes the amount of explosives, timing and near-source accelerogram records. The impulse time series is compared in the frequency domain to the double integrated accelerogram. The data recorded at CHNAR for this event are also included and indicate the relative small size of the seismic signals.

Group F events are associated with construction at the new international airport near Seoul. We conducted a limited study of a collection of seismo-acoustic events from the new airport. A comparative study of the waveforms from Group F was undertaken and provided precise L_g-P times that were used to estimate distance from CHNAR. This distance estimate was combined with seismic and infrasound back azimuth estimates to produce the event locations reproduced in Figure 4. Two event clusters were identified and the seismic waveforms were sorted into these two groups and compared. The similarity of high-frequency waveforms (8-16 Hz) in each group suggests that waveform coherence may be useful in comparing near-by events. These results also are suggestive of the importance of infrasound back azimuth estimates for improved event location. The difference in waveforms between the two groups may be reflective of the different propagation path effects. Alternatively, the differences may reflect blasting practices in the two regions.

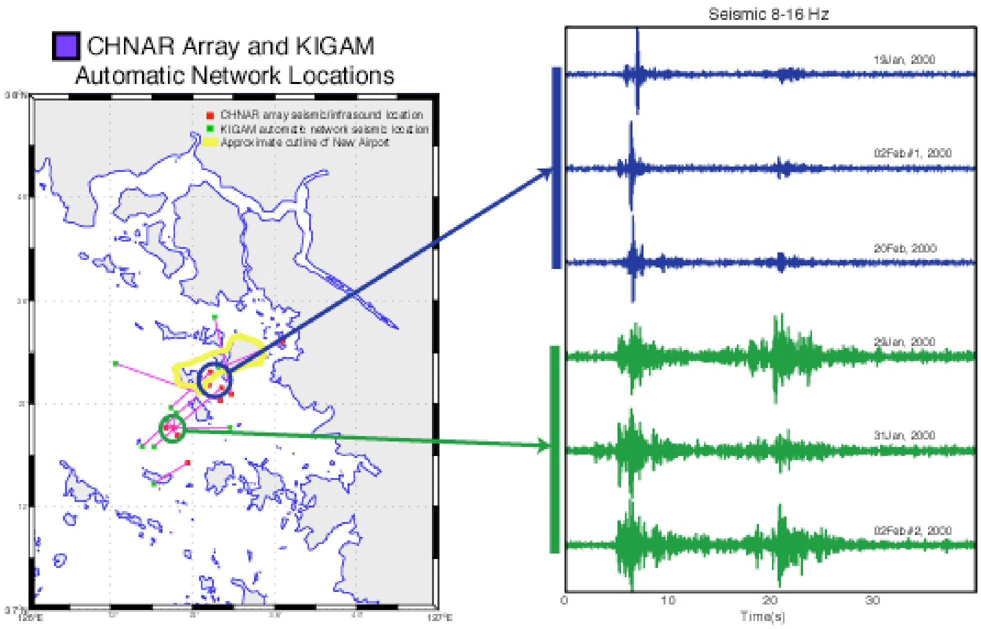

Figure 4: Seismo-acoustic event locations at the site of the new international airport near Seoul (Group F in Figure 2b). The events are divided into two groups (green and blue circles). The events from each group produce similar waveforms in the 8- to 16-Hz band.

Infrasound signals that accompany the seismic signals from the airport construction are illustrated in Figure 5. Two distinct source regions associated with the new construction were identified by the seismic data, and the accompanying infrasound signals are color coded to match. Infrasound signals from five events are shown in Figure 5. There is some indication that the infrasound waveform is characteristic of the source region as well. The infrasound signals for one event observed across CHNAR are plotted below right and illustrate high signal correlation in the 1- to 5-Hz band.

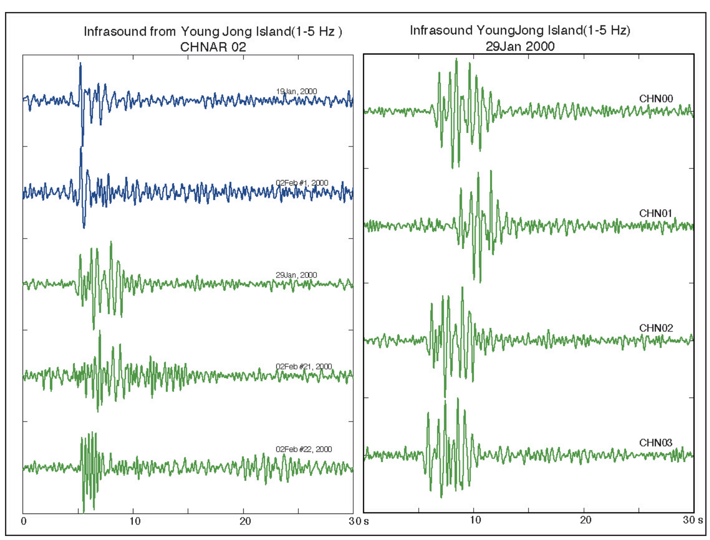

Figure 5: Single sensor infrasound signals from five of the seismo-acoustic events identified in Figure 4 are displayed in the left panel (Group F in Figure 2b). The color of the waveform corresponds to the event groups identified earlier. Signals recorded across the array for one of the events are reproduced in the right panel.

Infrasound Modeling

The seismo-acoustic array at CHNAR, South Korea, was used to evaluate all lone infrasonic arrivals for one week each in October and November 1999, and February, April, June, August 2000. Each infrasound arrival was processed for azimuth, time, phase velocity, and "type". Typically, there are one to two seismo-acoustic events per day observed. In contrast there are between 10 and 100 times more infrasound-only signals. The azimuth and time of arrival for these signals is summarized in Figure 6. The vast majority of events during the same 24-hour period occur during daylight hours suggesting man-made origin. The azimuths from which the signals propagate vary from month to month. The relatively high-frequency content (4-5 Hz and above) as well as the short signal duration and seismo-acoustic arrivals suggests short propagation path effects of less than 200 km.

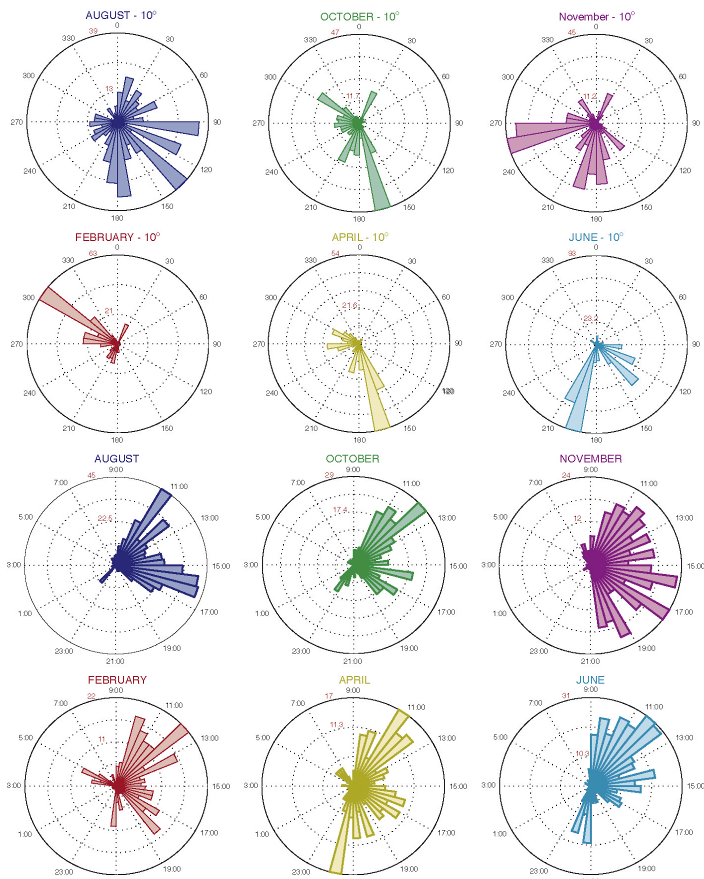

Figure 6: Summary of event back azimuth (top panel) and event arrival time (bottom panel) for the lonesome infrasound signals from August, October, November, February, April and June

An infrasonic modeling package, InfraMAP (Norris and Gibson, 2001), was used to model ray path arrivals with standard seasonally averaged atmospheric profiles. Most atmospheric modeling is done using HWM (Horizontal Wind Model) and MSIS (Mass Spectrometer, Incoherent Scatter) data sets. HWM and MSIS are comprehensive empirical global models of winds and temperatures averaged over each season for decades. Most often, the ray paths to be modeled are "tele"-infrasonic, rays that travel through and turn in the thermosphere, or the upper 20 km or so of the atmosphere. As the thermosphere is essentially stable over daily time periods, this assumption for propagation is valid. For this study, we are interested in the stratosphere and troposphere, essentially the area including and below the jet stream (40-50 km). To turn a ray, there must be an increase in velocity greater than the speed of sound near the surface to create ducts. Using these models, infrasonic ray tracing was completed for the Korean Peninsula. Figure 7 illustrates a typical result for HWM/MSIS ray tracing illustrating the first ground return at nearly 300 km.

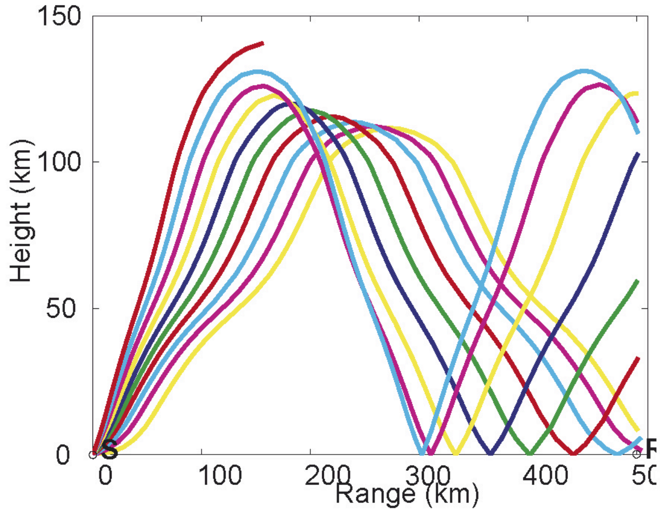

Figure 7: Ray tracing based upon average atmospheric models for the Korean Peninsula using the InfraMAP tool.

The lack of predicted returns within 300 km of the source motivated an exploration of the importance of actual meteorological data for the model troposphere. Such data were collected from OSAN, South Korea, the closest weather station to our array (Figure 8). InfraMAP calculates effective sound speed along a great circle path from source to receiver. Ray path calculations were completed along back azimuths spanning 360^{o} in order to quantify the azimuthal effects of the winds in troposphere.

The effective sound speed profiles were calculated using the following formula:

$C_{eff} = C_t + n \cdot v$ where

$C_t = ((a*R*T)/(m))^{0.5} = 20.07*(T)^{0.5}$ (Temperature contribution)

$n \cdot v$ = component of wind velocity in the direction of propagation (Wind contribution)

Monthly and daily averaged meteorological data from Osan are reproduced in Figure 9. These data were used in the ray tracing investigation of troposphere returns.

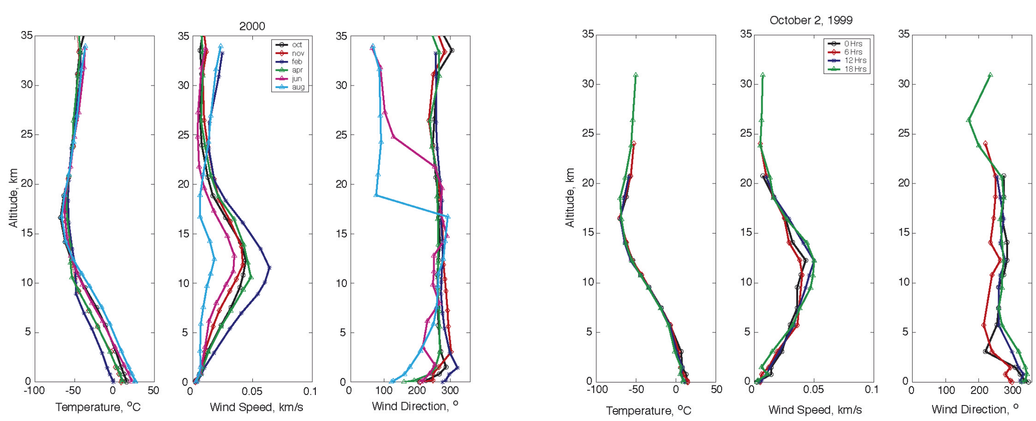

Figure 8a (left): Average monthly meteorological data including temperature, wind speed and direction as a function of altitude in the troposphere. 8b: Hourly meteorological data for 2 October 1999.

Ray paths created from using daily averaged meteorological data from August 4 are summarized in Figure 9. An example ray path is illustrated along with a pie chart illustrating the azimuths of predicted arrivals (red portions of the pie chart). The first arrival returns at about 18 km, much closer than the globally averaged data used in Figure 7, illustrating the possible importance of troposphere winds on short propagation distances.

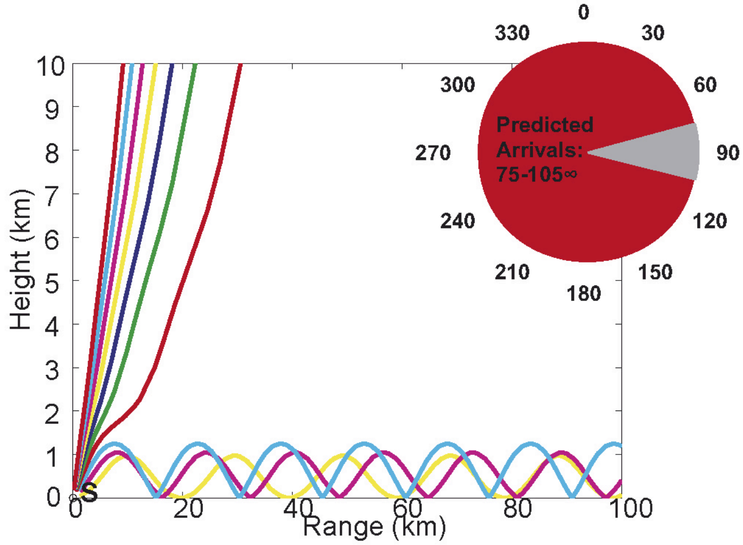

Figure 9: Ray tracing was conducted through a model in which the troposphere was replaced with a daily average wind data for August 4, 2000. The ray tracing produces arrivals that turn between 1 and 2 km and return energy to the ground a distances beyond 15 km for azimuths of 105-75^{o} (red portion).

Figure 8b illustrates that winds at low altitude can change on time scales of hours. In order to investigate the possible importance of short term temporal variation in troposphere wind patterns on short propagation paths, ray tracing was completed using the observed winds at two time periods separated by six hours (Figure 10) for August 4, 2000. Arrivals are predicted along low altitude ducts for each data set but the changes in the winds over the six-hour time period produce significant variations in the azimuths along which the low-altitude energy will propagate. These hourly data predictions are also different from that predicted by the daily averaged winds used to produce Figure 9. These numerical models suggest that detailed meteorological data may be necessary for the interpretation of short distance infrasonic arrivals (10-300 km). These models also suggest that the azimuth of infrasound observations may change over short time periods. One might speculate that intermittent observations from sources could be expected as a result of these meteorological effects.

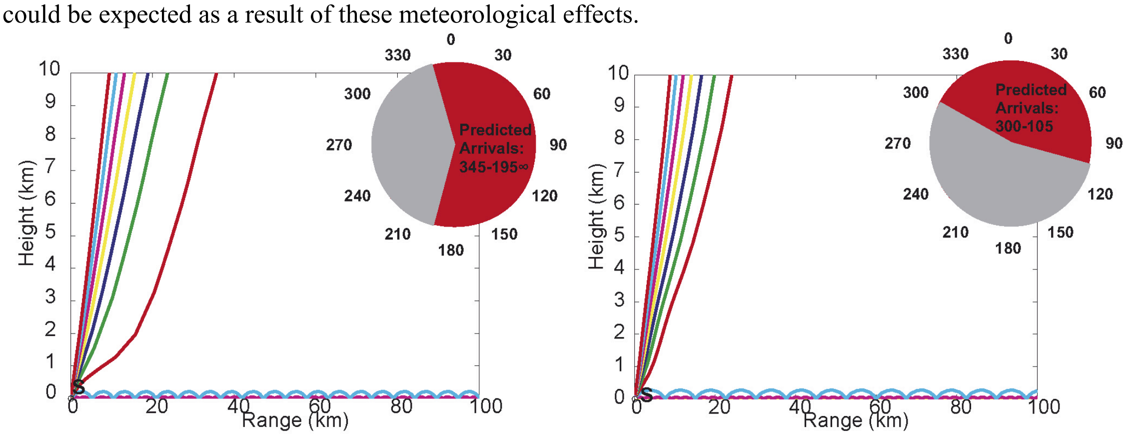

Figure 10a: Ray tracing for August 4, 2000, where the troposphere model is replaced with observed wind data for Hour 0. 10b: Ray tracing for August 4, 2000, where the troposphere model is replaced with observed wind data for Hour 6. There is a dramatic change in the azimuths that predict arrivals at short source-to-receiver distances.

CONCLUSIONS AND RECOMMENDATIONS

Ground Truth

Seismo-acoustic events are regularly observed at CHNAR. The seismo-acoustic array provides the opportunity to locate and characterize these events. Over two years, 2000 and 2001, a little less than one seismo-acoustic event per day was observed at the array. As illustrated in Figure 2, the vast majority of these events occurs within 200 km of the array. Additionally, the events are found to cluster into groups indicating that they are characteristic of man-made sources.

Several of the sources identified by the seismo-acoustic analysis were investigated as to generating mechanism. A ground truth database has been developed that indicates sources of seismo-acoustic energy include mining explosions and construction blasts. No acoustic signals have been associated with known small magnitude earthquakes.

Detailed ground truth on a number of mining explosions illustrates the dramatic effect that delay-firing has on peak amplitudes of the seismic phases. Synthetic models supported by close-in measurements suggest that delay-firing reduces the amplitudes of high-frequency regional phases by a factor of 10 to 100, thus explaining the small magnitudes for many of the Korean mining explosions.

A simple experiment was conducted in which seismic and infrasonic data were combined to produce a combined event location. The event distance was estimated using arrival time data at CHNAR. These events had accompanying infrasonic signals that were used to estimate the event back azimuth. This investigation focused on signals from construction blasts at the new airport near Seoul. The resulting event locations clustered into two relatively tight groups. The seismic waveforms for all events in each group were compared and produced strong correlation to frequencies in excess of 10 Hz. The seismic signals from the two groups, despite being relatively close to one another, were not correlated. These results suggest that infrasound data may be useful in refining event locations and may be combined with seismic signal coherence to further refine locations.

Infrasound Modeling

Many more infrasound signals are observed at CHNAR than seismic or seismo-acoustic signals. In order to assess the characteristics of these signals and investigate possible temporal variations in these signals, all acoustic signals occurring for one 7-day period in each of six months during the year spanning October 1999 to October 2000 were analyzed. The temporal occurrences of these signals suggest that they are man made as they only occur during daylight hours. The back azimuths for these signals show monthly, daily, and hourly variations as well.

The high-frequency nature of these signals (5 Hz and above) and the fact that seismo-acoustic signals with similar frequency content occur within 200 km of CHNAR suggest that the lonesome infrasound signals have propagated along relatively short paths. Ray tracing using the InfraMAP was undertaken in order to assess the possible paths these signals have taken. Average atmospheric models for the Korean Peninsula predict no arrivals within the 200-km range. The short paths suggested that variations in the temperature and winds in the troposphere might account for the arrivals, thus meteorological data was obtained and incorporated into the lower atmosphere model. Ray tracing through these models produces arrivals that return to the surface at close ranges (< 200 km). The meteorological data was taken on 6-hour intervals and further suggest that variations on these relatively short time scales may produce short distance propagation ducts that open and close. These numerical results are supported by hourly variations in observed azimuths for the lonesome acoustic waves. This suggests that the lack of an associated acoustic arrival with a seismic arrival cannot be used to rule out a surface explosion source.

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